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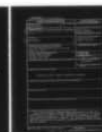
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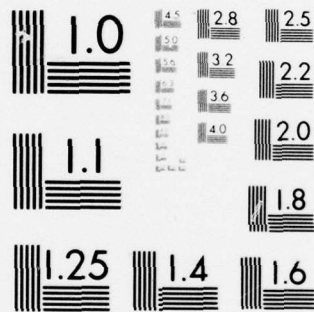
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FINAL REPORT PR 78-11-25

Research on Decision-Analytic Technology

R.V. Brown

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RESEARCH ON DECISION-ANALYTIC TECHNOLOGY

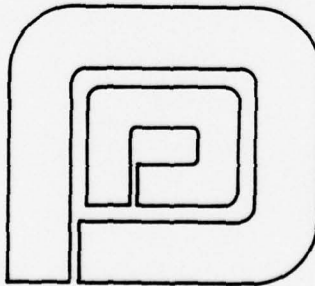
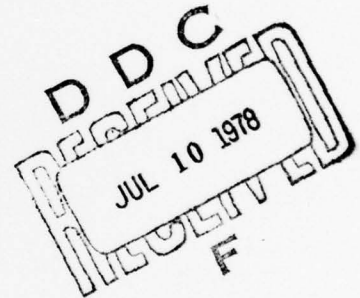
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May 1978



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This effort parallels two other research programs monitored by the Office of Naval Research and conducted by DDI: "Research on Advanced Decision Technology" funded by ARPA, and "Application of Decision Analysis Technology to Operational Decision Aiding at the Task Force Command Level" in ONR's Operational Decision Aids Project.

Tasks were undertaken in five general areas: method generalization; development of specific techniques; development of basic theory; behavioral research; and illustrative case studies. They resulted in 18 eighteen technical reports, ten working papers, and seven archival publications. (see references). Titles and abstracts of working papers are given in the appendix.

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RESEARCH PROJECT ON DECISION ANALYTIC TECHNOLOGY

1.0 INTRODUCTION

This report describes a research effort extending over two and a half years under contract N00014-75-C-0426. The primary objective of the program was to develop the technology in which decisions and inferences are made by individuals and implemented on a computer. The conceptual framework within which the decision aids are developed is personalist decision theory including Bayesian Inference.

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2.0 MAIN TASKS AND ACCOMPLISHMENTS

2.1 Methodology Generalization

Substantial effort was devoted to two tasks oriented toward developing the "state of the art" of decision analysis at a general level. These tasks were designed to make available to users, practitioners, and researchers in the field of decision analysis the insights and generalized experience acquired by DDI staff in the process of attacking a succession of real-world, practical problems.

2.1.1 Taxonomy matching - The first task was to develop a conceptual taxonomic framework within which the "state of the art" of applied decision analysis could be codified for the purpose of matching analytic approaches and techniques to different kinds of decision situations. The results of this effort are presented in a three-volume report (see references 11 & 12).

The first volume describes the conceptual framework within which experienced decision analysts can derive generalizations and communicate them to decision makers and inexperienced analysts. The framework consists of a three-way taxonomy: decision situations, analytic options, and performance measures.

Within this framework, a tentative and illustrative set of practical guidelines is presented to help decision analysis users and practitioners identify appropriate analytic approaches for any given decision situation. An attempt is made to suggest a taxonomic framework for codifying the state of the art of decision analysis, a language for expressing "matching generalizations" which associate the appropriate analytic option to a particular situation. This

language has three main components, each of which has an exhaustive numerical coding scheme.

The first component is a "situation taxonomy," listing about one hundred dimensions of a situation that might be relevant to a particular analytic choice. These dimensions include: the stakes involved in a decision, the reaction time available, and the clarity with which options, probable consequences, and values are perceived.

The second component is an "analysis taxonomy," according to which about one hundred decision-analytic choices can be located in an "analytic option space." Dimensions of the analytic taxonomy include: how much decision analysis is undertaken, how it is used, what type of model structure is involved, and what technique for probability assessment or consequence evaluation is employed.

The third component is a "performance measure taxonomy," listing about thirty measures of effectiveness which can characterize the analytic options. The same taxonomy can also be used to describe a situation by expressing the relative importance of the performance measures in the situation. Performance measure dimensions include: enhanced logical reasoning, cost, speed, convenience, and facilitated communication. This component serves as a mediating factor, implicit or explicit, in matching analysis to situation.

In this research effort, an attempt has been made to identify a few important and plausible matching generalizations based on the experience of practicing decision analysts. A few analytic options were selected to represent thousands of possibilities and to facilitate generalizations about when they should be exercised in the form of a taxonomy matching. A U.S. decision on whether to

export high-technology items to the Soviet Bloc is analyzed by using the taxonomic matching framework. Other illustrative material is also used throughout the report.

The second volume contains five case applications of the framework. The framework is used to explain the choice of decision-analytic techniques to apply to cases involving:

1. the problem of what foreign policy the U. S. should adopt in order to obtain more oil from a particular Mideastern country;
2. a decision faced by the president of an electrical equipment company of whether to purchase the defense market rights to a flight safety patent;
3. a project undertaken by the Naval Electronics Systems Command (NAVELEX) to apply the "Design-to-Cost" concept to an evaluation of proposed electronic warfare systems;
4. a research and development project to develop tactical decision aids for Navy task force commanders;
5. a study aimed at predicting NATO's response to actions taken by the Warsaw Pact countries.

The third volume contains detailed descriptions of the three taxonomies that comprise the framework.

2.1.2 Methodology notebook - The second major task was to develop a file of methodological insights stimulated by experiences of prosecuting case studies in the course of other contracts by DDI staff. Decisions and Designs, Incorporated, as a major part of its activity, conducts decision analyses of a number of major problems in the public and private sectors. The primary thrust of many of these projects is problem specific, either to help an individual or an organization perform their tasks more effectively or to explore the applicability of decision analysis technology in the context of a specific testbed.

The terms of the sponsoring contracts do not typically call for direct contributions to generalizable methodology. The cases, as developed for the sponsor, however, represent an indirect contribution to decision analysis methodology insofar as they represent an accumulated sample (uncontrolled and certainly non-random) of application experiences. They show, for example, how specific variants of multi-attributed utility models, Bayesian inference algorithms, Paretian models, and so forth, have been used to address specific problems, and with what results.

The potential for direct contribution to the state of the art of decision analysis is very great, however, if additional effort devoted to that goal accompanies each case study. The cases represent very rich sources of insights and material relevant to generalized contribution to the state of the -art, both in terms of operational methodology and more basic research.

Some such insights were written up as working papers varying in length from two to sixty pages; others be-

came the subject of specific tasks covered elsewhere in this report. Most remained as notes in an internal DDI file to be accumulated and built upon until they reach a point where they merit development as methodological generalizations or research proposals through which to reach a wider audience. Three technical reports and nine working papers are attributed to this task (see references 1, 3, 7, 8, 10, 15, 16, 17, 18, 23, 32, 34).

2.2 Development of Specific Techniques

As a result of activity under the methodology notebook task above, the need to develop special-purpose techniques for applied decision analysis arose along with ideas for their solutions.

2.2.1 Modelling subsequent acts - A challenge to conventional paradigms for modelling acts subsequent to the immediate decision was developed (see references 3 & 4).

When making a current decision, like choosing an experiment, a subject, S, will often take into account "subsequent acts" which he does not yet commit to. Common practice requires S to model them through preposterior analysis, which treats one act as certain, conditional on the intervening information modelled. This is not logically necessary since a coherent S would obtain the same expected utilities for his current decision if he properly conditioned utility of any selection of events (including subsequent acts). He could assess utility marginal on subsequent acts, or conditional on subsequent acts treated as uncertain events. The preposterior model is a special case of the latter where conditioning information is sufficiently modelled to imply subsequent act probabilities of zero or one. This study argues that attempts at preposterior modelling are often unsuccessful and have critically flawed much current

practice in decision analysis. Simpler approaches such as the "acts-as-events" model are intrinsically less dependent on restrictive assumptions and have been successfully applied to many real-world decisions.

This procedure is illustrated in the context of a Navy task force commander's decision situation, describes a prototype interactive graphic computer implementation of his procedure, and the results of a preliminary test and evaluation of it are presented.

2.2.2 Environmental indices - Techniques for developing of multi-attributed indices of environmental water quality were proposed as an example of more general applications of multi-attribute utility theory (see references 27 & 28).

This study developed an approach for scaling multi-attributed alternatives in the development of indices of water quality. The study, conducted in 1970-1971, was an early application of techniques developed for the general study of the assessment of the utility of multi-attributed alternatives, or simply multi-attribute utility assessment (MAUA). The work is recast here as a case study with emphasis on the steps involved in the application of the procedure.

The specific question addressed in this study was whether each different use for a water supply would require a special index, or whether an overall index would suffice. The study facilitated a test of the feasibility of applying proposed utility assessment methods to a complicated real-world problem. Developing such water quality indices requires establishing a suitable mathematical function defined for an appropriate set of parameters. This mathematical function assigns to a complex, multi-dimensional alternative (a sample from a surface body of raw water) a number which validly represent the quality of that water for a specific consumer population.

2.3 Basic Theory

In the course of solving a practical decision problem, it often happens that weaknesses--or at least areas needing further development--in the fundamental basis of decision analysis come to light. Three such opportunities were pursued, and each case combined the analysis practitioner's appreciation of the practical problem with the academic's immersion in the relevant discipline.

2.3.1 Value of decision analysis - The problem of how much decision analysis is worth to a prospective user is raised at least implicitly every time the tool is applied. But techniques for assigning values have not been developed for lack of a conceptual framework to develop them from. A Cambridge mathematician worked with DDI staff to develop such a framework and to begin developing operation algorithms for practical use (see references 13, 14, 35, 36).

This study explored methodological issues, especially logical and mathematical, in putting a dollar value to a proposed decision analysis exercise. It restricts attention to the direct value of the analysis in terms of impact on the decision analysed. It disregards indirect values (or costs) the analysis may have, however important these may be in enhancing organizational processes. Two alternative valuation instruments are identified, expressed in explicit mathematical form.

One approach is predicated on the assumption that there exists a correct ordering of immediate decision options for a given individual at a given period in time. It can be loosely defined as the result of infinite and impeccable analytic pains. This valuation algorithm involves assessing reduction in "expected irrationality cost" (comparable to "expected opportunity loss" in the valuation of information).

The second, less ambitious approach is based directly on the standard decision-analytic paradigm of comparing expected utilities with and without the proposed analysis. It requires fewer, if possibly more elusive, elicitations than the first approach.

A companion research effort approaches the problem of making such an instrument operational through "after-the-fact" valuation of three completed decision analysis exercises. In each case, an attempt is made to gain a hindsight value for the analysis with a view to facilitating "before-the-fact" valuation for analogous decision analysis exercises in the future.

Latter stages of the enquiry addressed:

the conceptual mathematical and graphical explication of some basic procedures;

an adaptation of the procedures to a real decision analysis; and

the notion of perfect rationality as a reference point against which to evaluate proposed analyses.

2.3.2 Reconciliation of judgmental incoherence - Different ways of modelling a problem often yield very different conclusions even when the model inputs come from the same source; this gives rise to a dilemma for the subject that the current status of decision theory does not address.

The dominant paradigm of formal decision analysis involves constructing models which force logical coherence between a subject's choice of action and his other judgments, probability and utility. However, it is by no means obvious

how an initially incoherent subject should reconcile his judgments to form a coherent decision model, nor how alternative ways of modelling a given probability or utility should be reconciled. There are, in general, any number of ways that the inputs to the models can be adjusted to yield coherent systems of judgment. How, in principle, should a single point in such reconciled systems be chosen?

A statistician from London University and a psychologist from Hebrew University worked with DDI staff to develop conceptual principles according to which judgmental incoherence can be resolved. They have developed an approach whereby a higher order of judgment is invoked bearing on the "precision" of the subject's original "readings." They consider both the case where all potential readings are taken and where some subset of readings is to be reconciled. A large part of the study is in preliminary draft form, pending the availability of funding for completion.

However, a special-purpose structure for use in the special case of probability assessment has been developed to the point of publication (reference 25). This paper investigates the question of how to reconcile incoherent probability assessments, that is, assessments that are inconsistent with the laws of probability. A general model for the analysis of probability assessments is introduced, and two approaches to the reconciliation problem are illustrated and discussed. In the internal approach, one estimates the subject's "true" probabilities on the basis of his assessments. Least-squares procedures for reconciliation are developed within the internal approach. In the external approach an external observer is introduced, who updates his own coherent probabilities in the light of the assessments made by the subject.

2.3.3 Pretesting innovation - The introduction (or modification) of a management system in an organization is often preceded by an effort to gather data from which it can be evaluated. The data may come from some kind of experiment, a conceptual simulation, or some more informal analysis of relevant past experience.

Experimental and other well-developed paradigms often prove unsatisfactory, or at least incomplete, as a basis for validating sequential decisions in the design of systems and other innovations, for example, the development of operational decision-aiding systems for the Navy. DDI and Cambridge University staff have made an exploratory attempt to develop a cohesive conceptual framework for testing such innovations (see references 15 & 16). A paper on this subject discusses how alternative testing procedures can themselves be evaluated by paying particular attention to analogous testing paradigms in the more established fields of science and engineering. Decision-aiding systems for naval command and control are used as an illustrative case.

2.4 Behavioral Research

The choice of technical approaches for decision analysis often involves taking a position on behavioral issues calling for experimental and other empirical research.

2.4.1 Group assessment experiments - Choice of alternative methods for eliciting probability assessments from groups of individuals calls for judgments about the circumstances under which one technique (such as Delphi) outperforms another (for example, Delbecq). Experimental work to establish such generalizations was performed in collaboration with Duke University staff (see reference 21).

A number of studies have shown that a consensus probability distribution, obtained by averaging together the assessments of individuals, typically outperforms almost all individual probability distributions. The present study evaluated several strategies for improving upon this averaging approach. These strategies provide for some type of interjudge interaction.

No between-procedure differences were obtained. In addition, a re-analysis of data from a previous study in which statistically significant between-procedure differences were obtained suggests that these differences were too small to be of practical significance to the applied decision analyst.

Based on these results and a review of the relevant literature, two conclusions emerge: (1) subjective probability distributions can be substantially improved by aggregating the opinions of a group of experts rather than by relying on a single report, and (2) from a practice standpoint, there is no evidence to suggest that the method used to aggregate these opinions will have a substantial effect on the quality of the resulting subjective probability distribution.

2.5 Case Studies

In order to test the effectiveness of the current "state-of-the-art" and to suggest and motivate new lines for development, the development of an effective decision-aiding technology calls for applications to live problems of national concern. A number of such case studies were supported through this contract. Each case involved at least one other government agency, either as a joint sponsor or as a source of funds.

2.5.1 Energy cases--Federal Energy Administration -

Three projects were funded by the Federal Energy Administration. One used the technique of decomposed error analysis for making inferences about domestic energy conservation behavior based on survey results. A second applied personalist analysis tools to the design and interpretation of studies of public response to solar heating. A third applied information evaluation techniques to the problem of assigning priorities to different types of research FEA might undertake (see references 5, 6, 19).

2.5.2 Foreign policy case--U. S. Government - A

decision-analytic comparison of alternative foreign policy strategies bearing on Mideast oil (funded by Rome Air Development Center) was adapted for use as a pedagogical case study in collaboration with Harvard Business School, where it is used to train managers in the application of decision analysis techniques (see reference 9).

2.5.3 System acquisition--NAVCROSSACT - Multi-attribute

utility analysis was applied to several defense procurement decisions involving system acquisition (see reference 26). Each application permitted the methodology to be further refined and made more generalizable.

In the spring of 1974 NAVCROSSACT was confronted with a problem which most computer service organizations are facing with increasing frequency--computer system workload saturation.

Although NAVCROSSACT agreed to conduct the competitive procurement in accordance with GSA's requirements, NAVCROSSACT wished to assess the impact of such a procurement upon the costs and level of services which it provides to its users and to evaluate ultimately the desirability of that course of action.

This study developed a formal methodology, a form of multi-attribute utility analysis, for conducting the evaluation, with features making it generally applicable for a wide range of procurement applications.

2.5.4 System acquisition--PMTTC - The purpose of this work has been to develop and implement a computerized Pilot Task Inventory appropriately structured and applied to the fighter version of the F18 aircraft. In doing so, a general methodology, applicable to other system acquisition problems, was developed (see references 29, 30, and 31).

The general approach was one of developing a Pilot Task Inventory by hierarchically decomposing the F18 pilot's tasks into clusters based upon mission, mission phase, mission sub-phase, pilot role, and utilized sub-system.

Two major problems involved in such an effort were: 1) the development of a valid, complete, computerized inventory, appropriately structured and readily usable by test pilots and 2) the development of a valid rating scale for use in rating the air system with respect to suitability for task accomplishment. The problems were solved by using multi-attribute utility assessment and a conjoint measurement rating procedure, respectively.

Special statistical analyses were devised which performed the following functions: 1) pinpointed areas of serious rater discrepancy; 2) pinpointed important F18 system deficiencies; 3) pinpointed important F18 system strengths. It was also possible to compare any two sets of individual pilot's ratings for important discrepancies, generate a mean set of ratings, and perform sensitivity analyses on the weights.

The MAUA assessment with its accompanying special statistics was shown to be of potentially great value in evaluating the F18 and other major aircraft systems during their test and evaluation phase.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The general research process represented by this contract consisted of taking ongoing experience in the practice of decision analysis as a starting point and using it to generate methodological generalizations and to stimulate further research of both a basic and applied nature. The object was to contribute to improved man-machine interface technologies.

Whether the specific technical and theoretical developments reported under this contract will have a major impact on the "state of the art" remains to be seen, since publication in the technical literature has been largely concentrated in the last six months of the contract. If the authors' contentions are borne out, at least one task (modelling subsequent acts) will have a major impact on the practice of decision analysis, and two will have a major impact on the theoretical formulation of the field (value of analysis and reconciliation of judgmental incoherence).

A further task (taxonomy matching) may lay the groundwork for the systematic codification of the "state of the art" of decision analysis--or parts of it. If the framework proposed recommends itself to other researchers and practitioners of decision analysis, their accumulated experience in the field may be used to help rapidly and efficiently select analytic approaches for particular situations.

Most of the tasks suggest avenues for additional productive research, not necessarily by the same investigators or research organization. The modelling of subsequent acts, the valuation of decision analysis, and pre-testing innovation are all topics which have been developed and disseminated to the point where other researchers can pursue them independently of the original researchers. All three have been published

in the professional literature. Taxonomy matching could be pursued independently, though findings on this task have not been widely distributed nor, in their current mode of presentation, are they easily accessible to researchers who have not been intimately involved in the project to date.

The task on the reconciliation of judgmental incoherence stands in most urgent need of additional effort by the original investigators. Although a report on a special aspect of the problem addressed has been prepared and will probably be published in the professional literature, much of the most general and fundamental material generated on this contract exists only in the form of voluminous but unpublished notes. It is conceivable that the synthesis, development, and publication of this material would represent a major breakthrough for the foundations of decision theory. This might pave the way for researchers to develop further special-purpose monographs.

However, in our opinion, the most important further research to be done by an organization such as DDI is to continue to generate entries for the "Methodology Notebook" from which much of our research and that of others has derived. There are a number of academic and other research organizations well qualified to pursue intensive theoretical, and in many cases technical, development (though it might be argued that DDI's close contact with live application of the technology contributes a special qualification to the latter). However, there are exceedingly few other organizations where the heavy ongoing interaction between technique and problems generates such an abundance of methodological sparks which, if immediately applied to reflective tinder, may set off major conflagrations of methodological innovation. We believe it is an essential ingredient for the balanced and practically oriented development of the "state of the art" that some analytic resources at least be devoted to such sparking activity.

APPENDIX

NOTES ON UNPUBLISHED WORKING PAPERS

Brown, R.V., The Credibility of Estimates. (December 1977).

Executives and others are frequently misled by conventional measures of research accuracy, usually in the direction of overconfidence. The author proposes a research appraisal tool which can be used without technical expertise to plan research or to assess the probable value of variables of direct interest.

Brown, R.V., V.N. Campbell, and P.H. Feuerwerger, Value of Eliminating Uncertainty Bearing on Ride-Sharing Options: A National Analysis. Decisions and Designs, Incorporated, September 1977. (Sponsored by ONR and the Federal Energy Administration).

Predicting the value of information sought by research before the research is undertaken leads to better funding decisions. Here, possible avenues for research in the area of ride-sharing are investigated in a "quick-and-dirty" attempt to predict their likely value by using the value of information technology of decision analysis.

Brown, R.V., V.N. Campbell, and D.J. Repici, Analysis of Residential Fuel Conservation Behavior: Memorandum of Findings, Appendices, Charts. Decisions and Designs, Incorporated, October 1977. (Sponsored jointly by ONR and the Federal Energy Administration).

From an analysis of consumer surveys and data from trade and industry, DDI has derived probabilistic estimates of temperature control and insulation responses to energy shortage in U.S. homes.

The data collection and analysis was conducted over a three-week period and included:

Analyzing of a Gallup home survey of 1,000 households nationwide;

Estimating the reporting, non-response and other biases and errors in the Gallup survey; and

Deriving independent estimates of the same target quantities based on a variety of sources: statistical, trade, survey and power utilities.

The sources of error in each approach were quantitatively assessed and combined using the technique of decomposed error assessment (DEA), and the estimates were pooled to derive single composite estimates and probabilistic margins of error for each target quantity.

Brown R.V. and D.H. Gustafson. Evaluating Decision Analysis Research Proposals: A Case-Illustrated Resource Allocation Procedure (WP-6). June 1977.

Decisions on how and where to spend research and development funds have long resisted systematic analysis. This paper describes a decision-analytic approach to the problems of comparing alternative research programs and of assigning research dollars among various projects or topics. The objective is to provide a workable tool that can help the manager of a funding agency to evaluate research proposals,

to assign his available resources as decisions have to be made throughout the year, and to plan complete agency programs.

A method is described, grounded in multi-attribute decision analysis and is illustrated by using the hypothetical example of a defense research budget for decision analysis research. An interactive computer program carries out the successive calculations.

Brown, R.V., J.E. Selvidge, and J.W. Ulvila, A Classification of Research Topics in Decision Analysis (WP5). June 1977.

It is often convenient to characterize actual or proposed research in a field like decision analysis according to a standardized set of categories and with a standardized terminology. An appropriate and clearly defined classification permits concise and precise communication of research activity among researchers and research users (such as decision analysts), for example, through catalogues, bibliographies, libraries, review, and technical papers.

The classification scheme proposed is one way of grouping actual and potential research activities in the field of decision analysis. The perspective taken in establishing the categories is that of an applied decision analyst and stresses the sorts of questions such an analyst would like to have answered by the research community. Consequently, the degree of detail in any category depends more upon the interests and priorities of the practitioner than the volume of past and current research. For example, "inference processes of individuals" is only one of thirty subtopics, although this topic certainly accounts for more than one-thirtieth of the published research in decision analysis.

Buede, D.M., Choosing the Most Beneficial Procurements with a Fixed Budget (WP-1). June 1977.

Decision analysts are often tasked to determine the relative value of several alternatives that receive their value as the result of a sequence of events. This sequence constitutes a dynamic process which provides the environment for the decision. The alternatives of the decision maker describe his ability to affect the outcomes of the dynamic process.

In lieu of a major breakthrough in the modelling of dynamic processes, this paper discusses how to improve our ability to construct and use static models.

Buede, D.M., Evaluating Dynamic Decisions with Static Models (WP-2). June 1977.

A procedure for eliciting a relative benefit scale for a set of possible procurements is described here. This benefit scale is a cardinal one but does not address the question of absolute benefit because the decision focuses on how to spend a given amount of money and not how much money to spend. The purpose of eliciting this benefit scale was to perform a cost-benefit analysis on the choice of procurements.

Keelin, T.W., III, Risk Preference for the United States (WP-3). June 1977.

Many of the important decisions we face today involve the prospect of very serious outcomes. Most dramatic, perhaps, are those involving war: even when the probability of war is small, its occurrence could be devastating. It is

therefore essential that decisions involving war, or any other serious outcome, be made on the basis of thoughtful, intelligent analysis.

When high stakes are involved, the important risks in dollars and lives must be carefully addressed. To do so explicitly requires establishing a risk attitude which can be communicated, understood, and applied in decision analysis. The purpose of this paper is to derive a utility function for expressing a risk attitude appropriate to the United States as a decision maker.

Selvidge, J.E., Assessment of Multi-Attributed Value Functions (WP-4). June 1977.

Two methods of evaluating decision outcomes for multi-attributed settings are contrasted and compared. The methods are the classical utility measure (under risk) of Von Neumann and Morgenstern, and the "Regret" assessment method frequently used by DDI in problems having a military setting. (See, for example, the "Warsaw Pact Attack" problem in Selvidge, Rapid Screening of Decision Options, DDI Report #76-12).

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